Monolithic flux transformer-coupled high-T_c dc SQUID magnetometers

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***Abstract*—$YBa_2Cu_3O_{7-x}$ based monolithic flux transformer-coupled high-T_c dc SQUID magnetometers operating up to 73 K have been realized. The devices are characterized by high values of the modulation voltage, up to 32 μV at 40 K. A minimal white noise level of 0.10 pT/√Hz was obtained above 200 Hz, and 0.64 pT/√Hz at 1 Hz and 55 K. The temperature dependence of the modulation voltage, the effective sensing area and the field sensitivity are discussed. Model-calculations have been performed to investigate high frequency resonances in the washer-input coil structure. Methods for damping are considered.**

I. INTRODUCTION

The magnetic field sensitivity of high-T_c dc SQUID magnetometers can be improved by reducing the effective input flux noise or increasing the effective sensing area A_{eff}, defined as the ratio of the flux coupled to the SQUID and the applied magnetic field. The latter is achieved most effectively using a planar flux transformer consisting of a large area pick-up loop and a multi-turn input coil, tightly coupled to the SQUID washer.

Various groups have presented sensitive flux transformer-coupled high-T_c dc SQUID magnetometers configured in a flip-chip arrangement [1]-[4]. A disadvantage of this configuration is the relatively large spacing between the washer and the input coil, resulting in a reduced coupling. This spacing is much smaller for monolithic flux transformer-coupled high-T_c dc SQUID magnetometers, first presented by Lee *et al.* [5] and Kromann *et al.* [6] based on template biepitaxial grain boundary Josephson junctions, and recently by us [7] based on bicrystal grain boundary junctions. Using the SQUID washer as the returnstrip of the input coil, the fabrication process is simplified to a level comparable with the fabrication of planar multi-turn coils, which is well established by now.

Here, we first describe in some more detail the electrical characteristics of the monolithic magnetometers. The temperature dependence of the modulation voltage, effective sensing area and field sensitivity are discussed. High frequency resonances occur in the washer-input coil circuit, leading to distortion of the flux-to-voltage transfer and presumably to excess noise. Based on a model developed by Enpuku *et al.* [8] the origin of resonances and possibilities for damping are investigated.

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II. DESIGN AND FABRICATION

The design and fabrication of the monolithic high-T_c dc SQUID magnetometers have been described in detail in [7]. The devices are manufactured on $SrTiO_3$ bicrystals with a symmetric 24° [001] tilt grain boundary. A four layer concept is used, in which the 5 μm wide junctions are situated in the 140 nm base $YBa_2Cu_3O_{7-x}$ layer, which is covered with a 250 nm insulating $SrTiO_3$ layer and a 400 nm $YBa_2Cu_3O_{7-x}$ top layer, out of which the multi-turn input coil is formed. Ti-Au contacts are used for electrical characterization. In the fabrication process, the definition of the junctions is left as the final step to avoid degradation resulting from subsequent processing steps.

The measurements described here were performed on a dc SQUID with a self-inductance L = 125 pH, coupled to a 6½ turn input coil with 15 μm wide windings, separated by 5 μm (Sample C in [7]). In the center of the SQUID the input coil is shorted to the washer. The washer is connected to a terminal of the pick-up loop, which has a sidelength of 8.5 mm and a width of 1025 μm. The other end of the pick-up loop is connected to the outermost winding of the input coil. The effective sensing area of the SQUID, calculated from the geometry, is 1.3 mm^2.

III. ELECTRICAL CHARACTERISTICS

SQUID operation in a flux locked loop was obtained up to 73 K, limited by the critical temperature T_c of the junctions. An I_cR_n product of 0.3 mV at $T/T_c = 0.2$ was measured, which is 7 times smaller than the value we normally obtain for 24° bicrystal grain boundary junctions at the same value of T/T_c. A reason for this may be diffusion of Ti in the grain boundary during the deposition of the $SrTiO_3$ layer. The normal state resistivity is relatively high, $\rho_n = 5\times10^{-8}\ \Omega cm^2$, independent of temperature. Fig. 1 shows the voltage versus applied magnetic flux for various values of the bias current at 65 K. The modulation is perfectly periodic and no influence of flux penetration in the junctions was observed, even with over 100 flux quanta coupled to the SQUID. A phase shift is found for the modulation with respect to the sign of the bias current. This is mainly attributed to the coupling of magnetic flux to the flux transformer by the bias current leads of the SQUID. Also an asymmetry in the critical currents of the junctions

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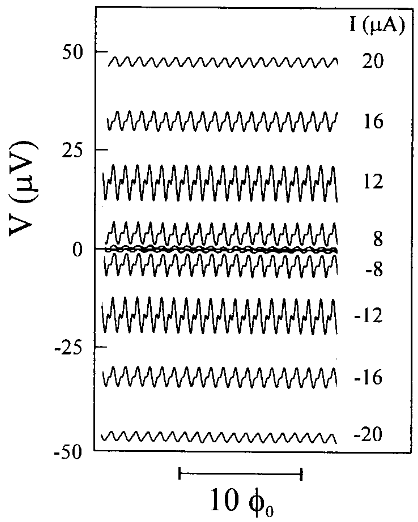

Fig. 1. Voltage V versus applied magnetic flux ϕ for various bias currents at 65 K.

may contribute to it. Although the V-ϕ characteristics are perfectly periodic, they are not smooth. The kinks in the curves are attributed to the interaction of the Josephson oscillations with high frequency resonances occurring in the transmission line structure formed by the input coil and the SQUID washer [9]. Resonances are further described in section V.

Fig. 2 shows the amplitude of the voltage modulation ΔV as a function of temperature. The maximum ΔV we have observed is 32 μV at 40 K, whereas at 70 K, $\Delta V = 5$ μV.

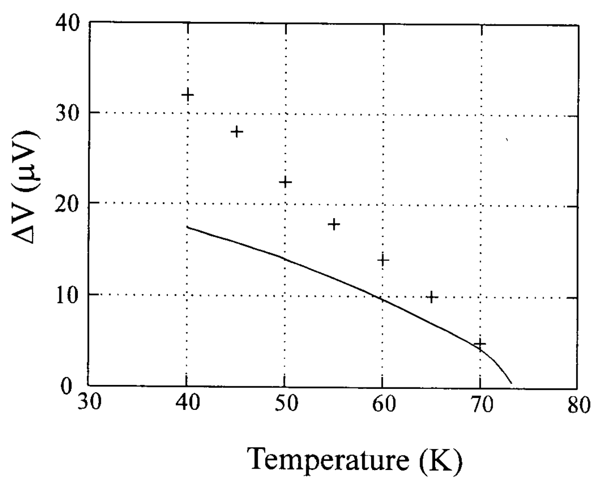

Fig. 2. Measured modulation voltage ΔV (+) and modulation voltage calculated according to eq. (1) (line) as a function of temperature.

These are the highest values reported thus far for monolithic flux transformer-coupled high-T_c dc SQUID magnetometers. For a given I_cR_n product and screening parameter β_L, the attainable ΔV, not taking the junction capacitance into account, is given by [10]:

$$\Delta V = \frac{7}{\pi^2}\frac{I_cR_n}{1+\beta_L}\left(1-3.57\frac{\sqrt{k_BTL}}{\varphi_0}\right) \qquad (1)$$

At all temperatures the observed modulation voltage is higher than the value calculated from eq. (1). This is attributed to the influence of the junction capacitance.

The temperature dependence of the effective sensing area has been investigated. Fig. 3 shows the mutual inductance M between an external magnet coil and the SQUID as a function of temperature. This quantity is proportional to A_{eff}. Beside the values for the flux transformer-coupled dc SQUID magnetometer also those for an autonomous dc SQUID with comparable dimensions, (Sample A in [7]), are given. The latter values have been multiplied by the temperature independent flux transformer gain (=72) in order to make comparison easier. The observation of a nearly temperature independent flux transformer gain is in correspondence with results reported for flip-chip magnetometers [11].

A_{eff} increases slightly with increasing temperature. The thermal expansion of the $SrTiO_3$ substrate is negligible in the temperature range under investigation and can therefore not account for the temperature dependence of A_{eff}. Instead, the temperature dependence of the London penetration depth λ is presumed to be the determining factor. Keeping in mind the

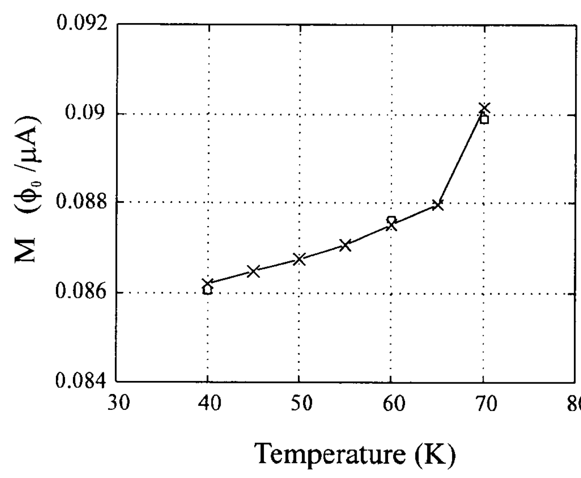

Fig. 3. Temperature dependence of the mutual inductance M between the magnet coil and the SQUID for the flux transformer coupled dc SQUID magnetometer (cross) and the autonomous dc SQUID (box). The latter values have been multiplied with the temperature independent flux transformer gain for ease of comparison.

temperature independence of the flux transformer gain, it is concluded that the increase of A_{eff} is due to the increase of the SQUID (hole) inductance caused by the increase in λ.

IV. Field Sensitivity

Noise measurements, of which first results were already presented in [7], have been carried out more elaborately. Fig. 4 shows the effective flux noise spectral density at 55 K. The white noise level found was 62 $\mu\phi_0/\sqrt{Hz}$ above 200 Hz, corresponding to a magnetic field sensitivity B_n of 0.10 pT/$\sqrt{Hz}$. At 1 Hz, the effective flux noise is 400 $\mu\phi_0/\sqrt{Hz}$, corresponding to $B_n = 0.64$ pT/$\sqrt{Hz}$. These are the lowest noise values reported thus far for monolithic magnetometers at these frequencies. The temperature dependence of the noise is shown in Fig. 5. The white noise level does not depend strongly on temperature below 60 K.

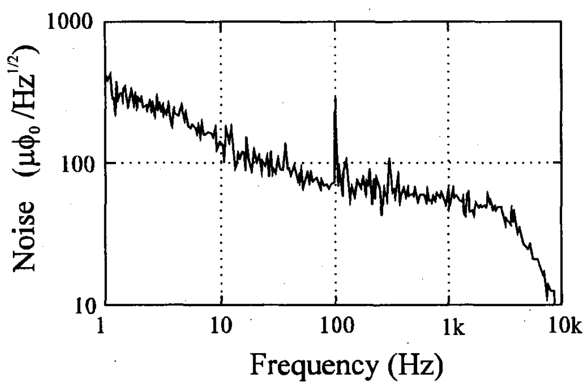

Fig. 4. Frequency spectrum of the noise at 55 K.

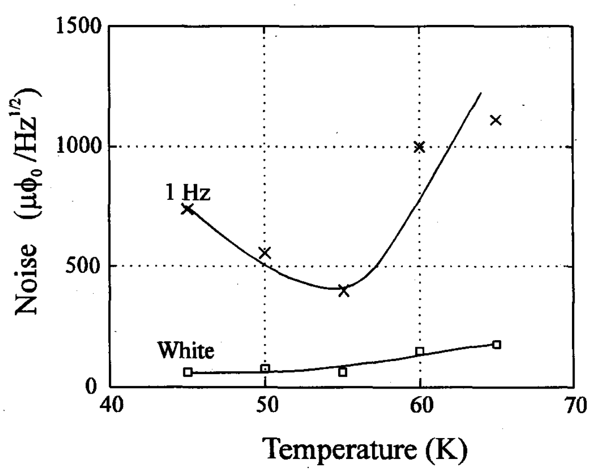

Fig. 5. White noise level and noise measured at 1 Hz as a function of temperature.

The 1/f noise has a minimum at 55 K. The increase of the low frequency noise below this temperature is attributed to increased critical current fluctuations, as is also observed in autonomous dc SQUIDs. The increased 1/f noise above 55 K may result from increased vortex motion in the multi-layer device. Due to the irregularities in the flux-to-voltage characteristics, application of the bias current reversal technique, by which 1/f noise due to critical current fluctuations is suppressed, resulted at all temperatures merely in an increase of the white noise level, to such an extent that a reduction of 1/f noise could not be discerned.

V. Resonances

A model to describe high frequency resonances in the SQUID, tightly coupled to the multi-turn input coil has been developed by Enpuku *et al.* [8]. With this model the complex impedance Z_{AB} 'seen' by the junctions is calculated. We have applied this model for our high-T_c dc SQUID magnetometers. In the calculations, a relative dielectric constant $\varepsilon_r = 800$ is presumed for the insulating $SrTiO_3$ [12]. The quality factor Q of the transmission line structure we presumed to be 50. Fig. 6a shows the frequency dependence of the absolute value of Z_{AB} for the undamped case. The peaks in the curves represent the resonance frequencies of the parallel circuit formed by the SQUID inductance and the transmission line structure consisting of the input coil over the washer. The minima correspond to the situation where exactly (2n+1) times a quarter of a wavelength fits in the transmission line structure.

Qualitatively the frequency dependence of $|Z_{AB}|$ resembles that for classical magnetometers. A main difference is the low frequency at which the resonances occur, due to the high dielectric constant of the $SrTiO_3$ layer. A consequence of this is that at any practical SQUID voltage, problems with input coil resonances are expected, as is indeed observed for our magnetometer devices.

Up to about 4 GHz, the resonances are confined to the input coil windings ('input coil resonances'). Above this frequency this is no longer the case and the washer and the input coil can be regarded as parallel plates ('washer resonances'). In a similar way as was described in [8], the input coil resonances can be damped using an R_x - C_x shunt between the washer and the outermost coil winding. For proper damping, R_x should be of the same magnitude as the characteristic impedance Z_0 of the transmission line structure. For the high-T_c magnetometer discussed above $Z_0 \approx 0.25\ \Omega$. The capacitance C_x is used to block the low frequency Johnson noise originating from this resistance. Were it not used, the effective flux noise due to R_x would be about 25 $\mu\phi_0/\sqrt{Hz}$. The effect on Z_{AB} of the application of an R_x - C_x shunt is shown in Fig. 6b. Obviously the input coil resonances are nicely damped. This method does not affect the washer resonances. Technologically less complicated is the use of a damping resistor R_d in parallel with the SQUID inductance. Fig. 6c shows the effect of this on Z_{AB} for $R_d = 0.1\ \Omega$. The effective input flux noise resulting from this resistor is calculated to be 10 $\mu\phi_0/\sqrt{Hz}$, which is acceptable for our purpose.

First experiments with damping resistors are presently being carried out. Results on this will be presented elsewhere.

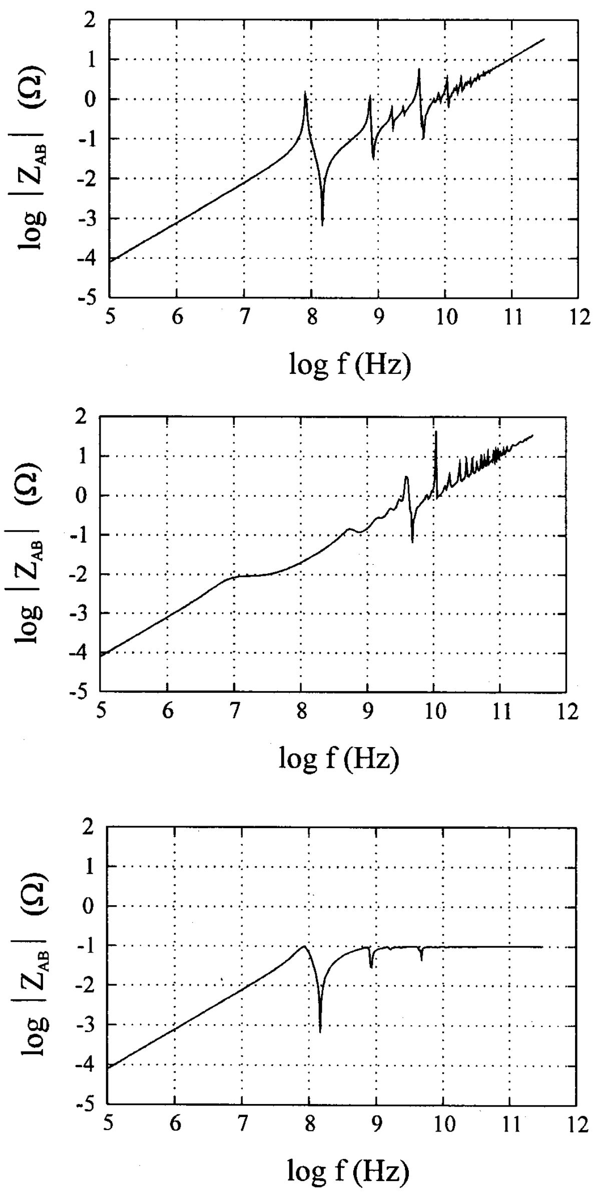

Fig. 6. Absolute value of the impedance Z_{AB} 'seen' by the junctions in the monolithic flux transformer coupled high T_c dc SQUID magnetometer; (a) with no shunts applied, (b) with an RC shunt between the input coil and the SQUID washer (R=0.25 Ω, C=100 nF) (c) with a damping resistor R_d connected in parallel with the SQUID washer (R_d = 0.1 Ω).

VI: Conclusions

In conclusion, monolithic flux transformer-coupled high-T_c dc SQUID magnetometers have been fabricated, operating up to 73 K. The devices are characterized by high modulation voltages. The effective sensing area increases slightly with increasing temperature, due to the increasing SQUID (hole) inductance caused by increasing λ. The white noise level decreases slightly with decreasing temperature. A minimum value of 62 $\mu\phi_0/\sqrt{Hz}$ has been measured. For the low frequency noise a minimum value of 400 $\mu\phi_0/\sqrt{Hz}$ is observed at 55 K. Due to the high ε_r of the insulating $SrTiO_3$ layer, input coil resonances occur at relatively low frequencies. The characteristics of the SQUID can be improved using an insulator with lower ε_r or a damping resistor.

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